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Researchers Use SMARTS to Explore an Uncommon Phenomenon Found in Rocks Under Stress

Cool a piece of marble, or any rock for that matter, and you would expect its stiffness to increase over time like that of metals, plastics, or even taffy candy. But a rock is different. No matter what type of stress is applied (e.g., temperature, pressure, shock waves), a rock initially *softens* before it behaves like other materials; recovery in rock is *nonlinear*. On a grander scale, this same initial softening response is observed by monitoring how aftershocks propagate in a region of the earth recovering from a massive earthquake. The underlying microscopic mechanisms for this unusual behavior are not clearly understood. Some of these mechanisms, such as twinning, defect migration, phase transitions, and texture relaxation — to name a few — have been suggested but not yet confirmed on the observed time scales and with the right nonlinear characteristics. However, scientists at Los Alamos National Laboratory may be closer than ever to determining a common mechanistic basis in stressed rock that gives rise to an initial softening and then nonlinear behavior upon recovery.

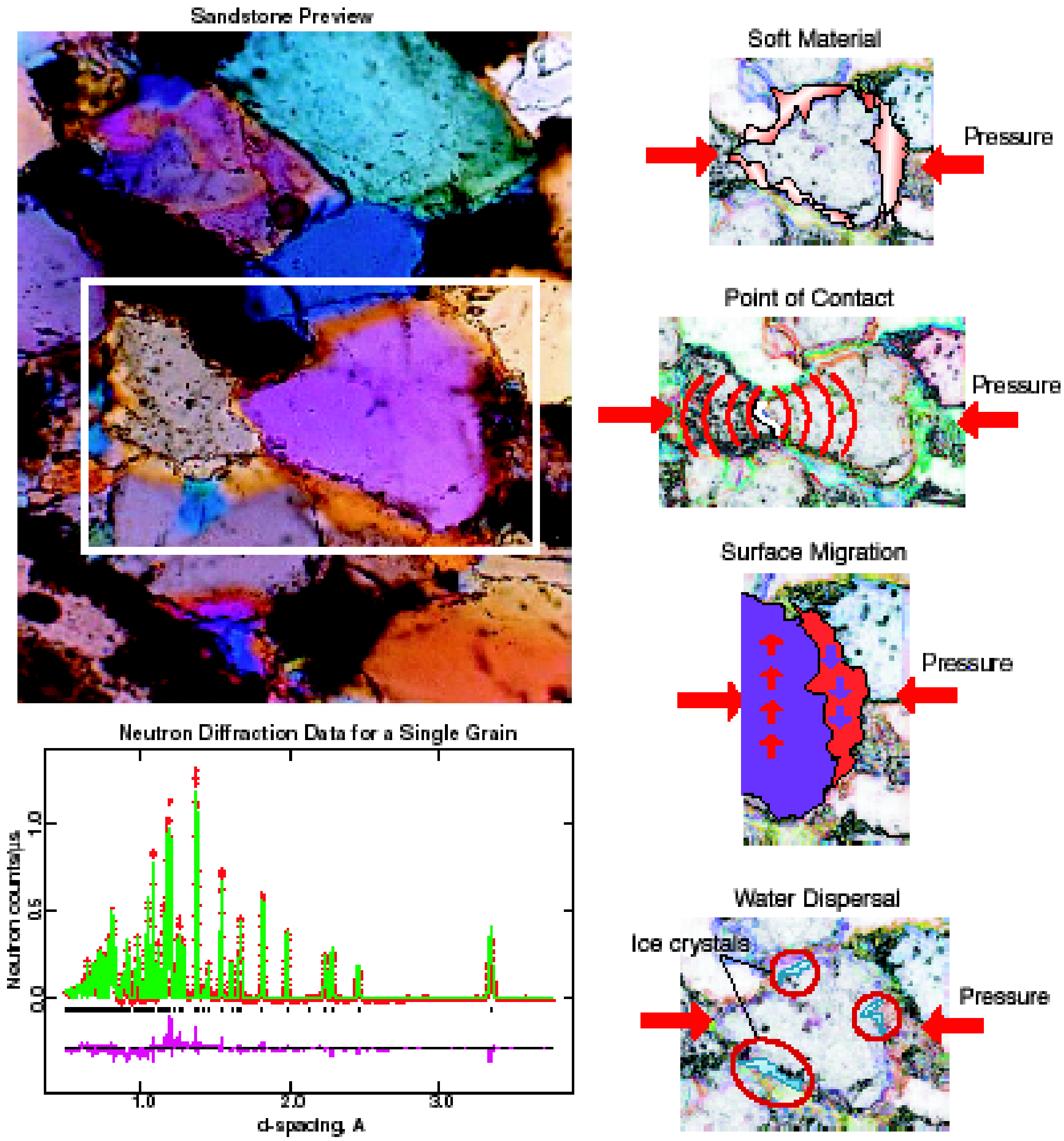

Fig. 1. *Polarized-light micrograph of Berea sandstone (average grain size 100 microns) showing quartz grains (colors) and clays and voids (dark areas) between grains. Rietveld analysis is shown below the photomicrograph. The four right-hand side figures illustrate some suggested microscopic mechanisms for the unusual macroscopic behaviors observed.*

Jim TenCate (EES Division), Tim Darling (MST Division), and Sven Vogel (LANSCE Division) are analyzing neutron-scattering data recently obtained on SMARTS to determine the response and recovery of single-phase, fine-grained rock samples subjected to a load stimulus. The recent experiments on SMARTS, and future experiments on HIPPO, are aimed at understanding the underlying microscopic mechanisms in rocks that give rise to an initial softening response to applied stress and then to a subsequent nonlinear recovery. To accomplish this goal, they must show correlation between microscopic and macroscopic dynamic responses in rocks to applied stress. Deformation processes occurring deep within the Earth take millions of years. But on instruments like SMARTS and HIPPO, scientists can study the behavior of memory effects (i.e., long-time strain recovery) in terms of applied environmental conditions — temperature, shock waves (acoustics), stress — with resolution on the scale of minutes! SMARTS was chosen because it has the capability to measure macroscopic stress-strain response while simultaneously using neutrons to observe what is happening on the atomic scale. HIPPO was chosen because it has extremely high neutron flux and a large number of detectors that allows scientists to observe the evolution of time-dependent effects in (near) real time.

When stress is applied to any material, the material experiences a change in dimension, volume, or shape. This change, or deformation, is called strain. End-point memory is the ability of the material to return, or recover, to its original state when the stress is released. In the recent experiments on SMARTS, a uniaxial load (compressive stress) was incrementally applied to (mostly) quartz sandstone samples. During this process, the interior microscopic strain response of the samples to the applied stress was measured via neutron scattering. Neutrons are ideal probes in these types of diffraction studies because they can easily penetrate rocks and reveal properties of the bulk interior material, whereas x-rays, for example, can only measure near-surface regions.

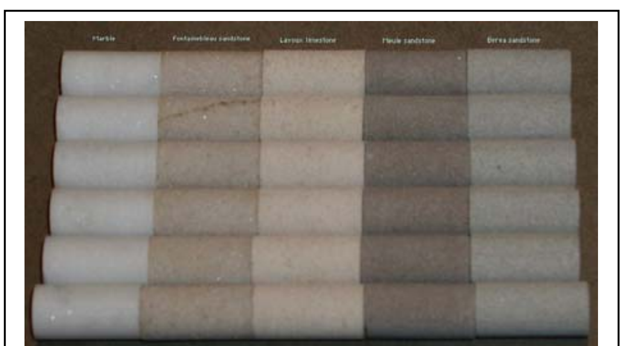

Fig. 2. *Cylindrical samples of single-phase, fine-grained rocks were used in the SMARTS experiments.*

With HIPPO, the researchers will collect acoustic, strain, thermal, and neutron-scattering data *simultaneously* to correlate microscopic and bulk effects following an applied environmental change. HIPPO has a high data-collection capability (high count rate) that enables researchers to take, in a sense, *snapshots* of the (local) atomic arrangement of samples undergoing some change in their environment *as a function of time*. Cylindrical samples of single-phase, fine-grained rocks (with diameters of 5 to 10 mm and lengths of

5 to 10 cm) have been prepared and will be studied in time-dependent mode under applied changes (i.e., a temperature difference; a burst of high-amplitude acoustic energy; and an applied, then released, static load). The researchers will simultaneously measure macroscopic responses to the changes with temperature sensors, a low-amplitude acoustic resonant probe, and strain gauges. The average and local atomic structures of the samples during the deformation process will be determined by both Rietveld analysis (a data-refinement technique for structural studies) and pair-distribution-function analysis (a real-space approach that characterizes amorphous structure). The information obtained from these experiments will be applied to mathematical models for the behavior of bulk rocks for seismic-wave propagation and stress response. Moreover, the basic deformation processes under study in these experiments are common to many material types, and therefore the results may lead to detailed models of mechanical responses for the detection of damage in materials as diverse as concrete and hardened steels.

The methods used in the SMARTS experiments provided information about the lattice strain response of *specific* grain orientations with respect to load. The scattering data are currently being analyzed and correlated with existing nonlinear acoustic data to determine which atomic-plane-level constituents of the samples are active in nonlinear processes. The initial results may already provide constraints on how much of the strain deformation occurs in the quartz and how much appears in the grain-boundary and *inter*-grain structure. Because previous measurements have not allowed the integrated characterization that these neutron tools allow, details of strain deformation is very poorly quantified (and mostly unknown) in rock mechanics. Further analysis is currently under way.

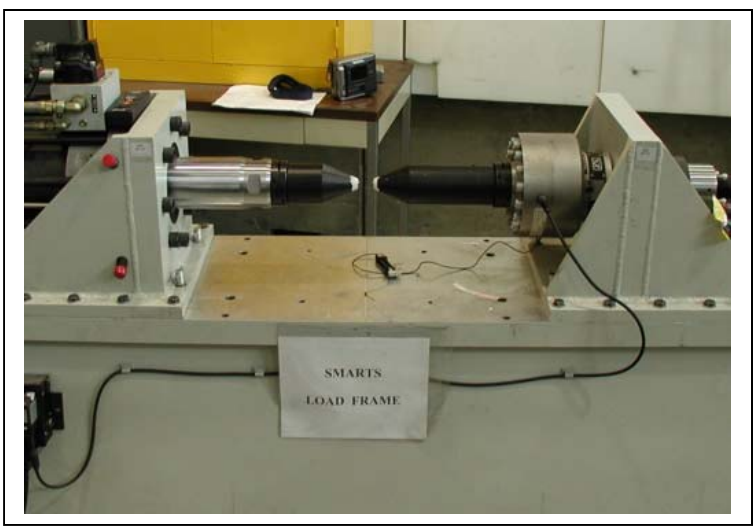

Fig. 3. *SMARTS load frame (custom-built for LANSCE by Instron). The rock samples are placed between the anvils and compressed to a specified pressure. The pressure is then gradually released, and the process is repeated.*

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